# RISKS FROM SOLAR PARTICLE EVENTS FOR LONG DURATION SPACE MISSIONS OUTSIDE LOW EARTH ORBIT

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## Introduction

The Integrated Medical Model (IMM) simulates the medical occurrences and mission outcomes for various mission profiles using probabilistic risk assessment techniques. As part of the work with the Integrated Medical Model (IMM), this project focuses on radiation risks from acute events during extended human missions outside low Earth orbit (LEO).

Of primary importance in acute risk assessment are solar particle events (SPEs), which are low probability, high consequence events that could adversely affect mission outcomes through acute radiation damage to astronauts. SPEs can be further classified into coronal mass ejections (CMEs) and solar flares/impulsive events (**Fig. 1**). CMEs are an eruption of solar material and have shock enhancements that contribute to make these types of events higher in total fluence than impulsive events.

**Solar Events**

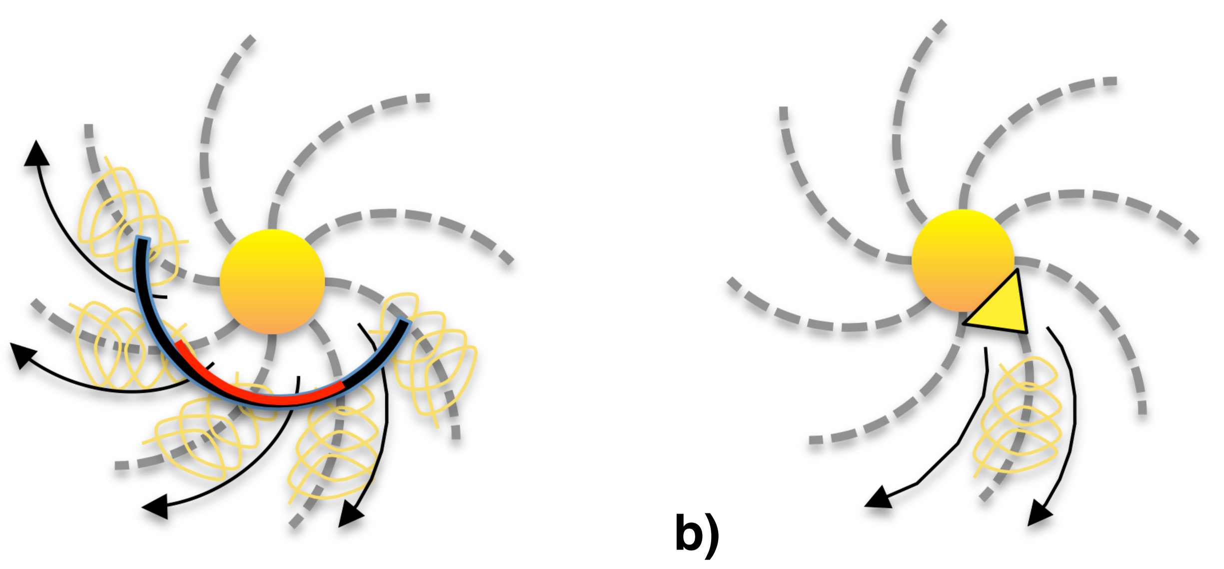



**Fig. 1:** Different classes of solar events include **a)** coronal mass ejections with shock enhancements that arrive gradually, but contain much more mass than **b)** impulsive events such as flares. Both classes of events travel along magnetic field lines as indicated in the figures. Adapted from Understanding Space Weather and the Physics Behind It by Delores Knipp, 2011.

For assessment of risks from CMEs outside of LEO, there are few models or data that cover this part of space directly, making it important to include mission profile choices in radiation risk assessment. This work continues the effort to add a radiation risk element in the IMM for long-duration missions outside LEO, looking specifically at missions to and from Mars.

## Methods

As in previous work on this project, this model utilizes a hazard function, which models the chance of an SPE occurrence for an averaged solar cycle of 4,000 days with solar maximum having a higher probability of SPE occurrence. This hazard function is then combined with a Monte Carlo approach that adds in the effect of orbital location on SPE occurrence. The result is that the highest chance of a damaging SPE is at solar maximum during a transit closer to the Sun.

The implementation of this model has been continued in MATLAB® to allow for integration of the radiation element with the remainder of IMM, serving as a cross-disciplinary tool.

Since this work was last presented, new additions to the model have primarily focused on adding severity probabilities and decreasing computational time as possible. In order to add severity levels, research was conducted into historical solar events, looking specifically at space age events. Prior to the space age, events can be inferred from historical records or nitrate levels, but the literature is conflicting on their use and so are not included in this study.

Since IMM focuses on worst or best case scenarios, the events analyzed were those that could be of the level to cause acute radiation effects. Events such as those from August 1972 and October 1989 are considered significant, while events just making the NOAA event list with 10 pfu do not.

For this iteration of the model, a cutoff of 1 x $10^9$ particles per $cm^2$ at 30 MeV was used since these events are more likely to be CMEs, and those above this limit can cause acute radiation effects of the level that would severely disrupt a mission. From analysis of historical events from NOAA and review articles, this came to approximately 4 percent of the total historical space age events.

**Proposed Mars Mission Profiles**

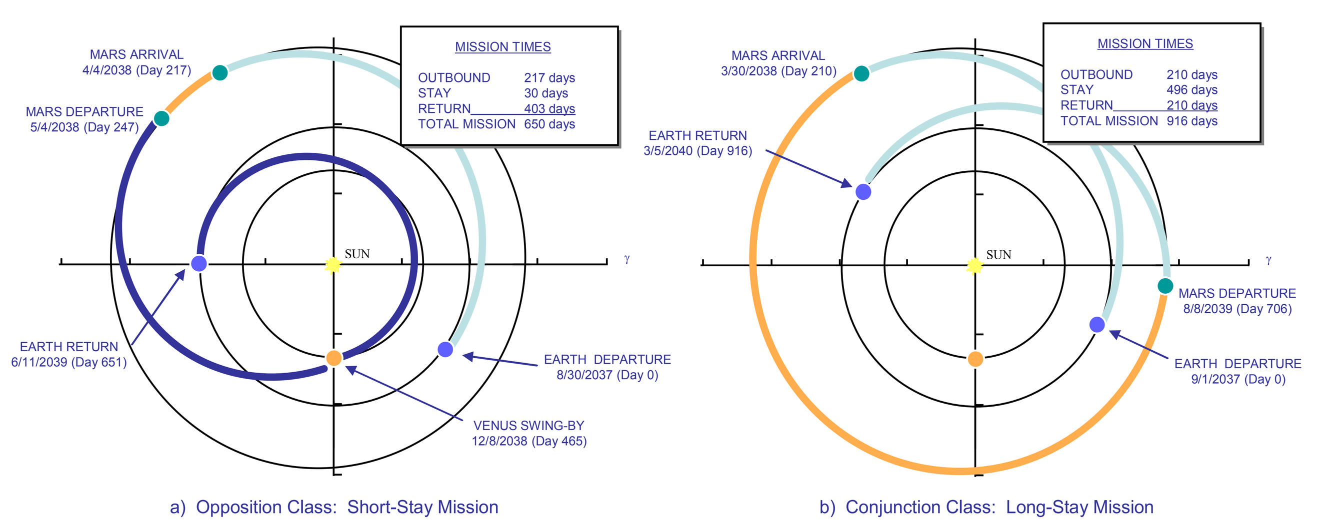



*Fig. 2:* Proposed long- and short-stay Mars mission trajectories with launch dates, which fall mid-range in the solar cycle. The work presented here assumes solar maximum. From: "Human Exploration of Mars: Design Reference Architecture 5.0", NASA-SP-2009-566.

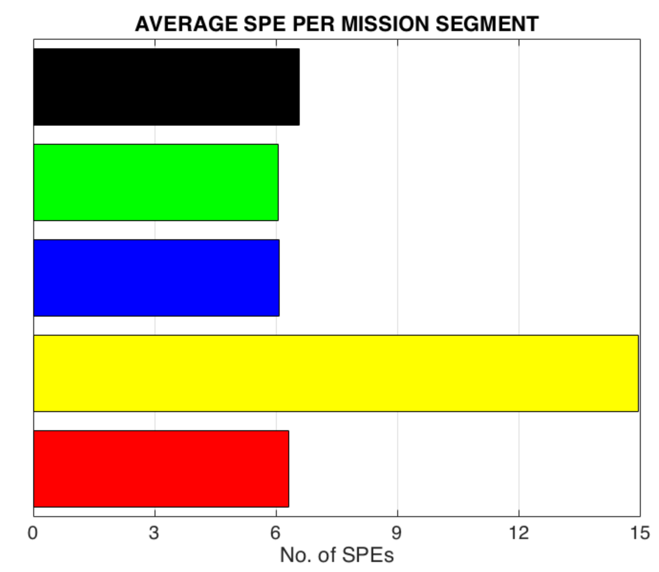
As with previous work, this model is designed to simulate the risks associated with NASA's Mars design reference architectures (**Fig. 2**). The Venus swing-by case is of special interest out of the 2 pairs of Mars out/inbound transits due to the number of days spent in deep space and closer to the Sun. Additionally, a comparison test case was developed for a mission profile at geostationary Earth orbit (GEO) for 183 days since the data used in this model is from satellites at geostationary orbits. For each of the 5 cases, chances of SPEs at levels above the $10^9$ criterion were evaluated and overall SPEs counted for a mission.

## Results

As expected from the data, the portion of SPEs that account for those above $10^9$ particles/$cm^2$ out of the total follow similar trends, dependent on mission time (**Fig 3**). Further analysis shows that the larger events account for approximately 3 percent of total events on average, but there is significant uncertainty in this value since the standard deviation in this average value is approximately 6 percent.

As the model includes the effect of increasing distance from the Sun, which reduces the likelihood of larger events, this slightly smaller proportion is expected as compared to 4 percent as an input to the model. What was somewhat surprising is that the maximum number of events above the threshold are only one more for the Venus swing-by case, showing that higher numbers of those events become increasingly unlikely based on the data input to the model.

**SPE Occurrences During Mission Segments**




a)

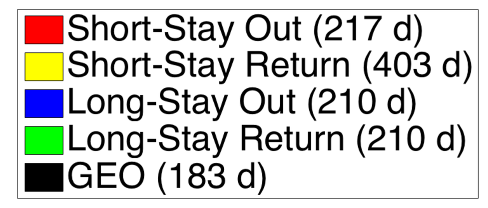
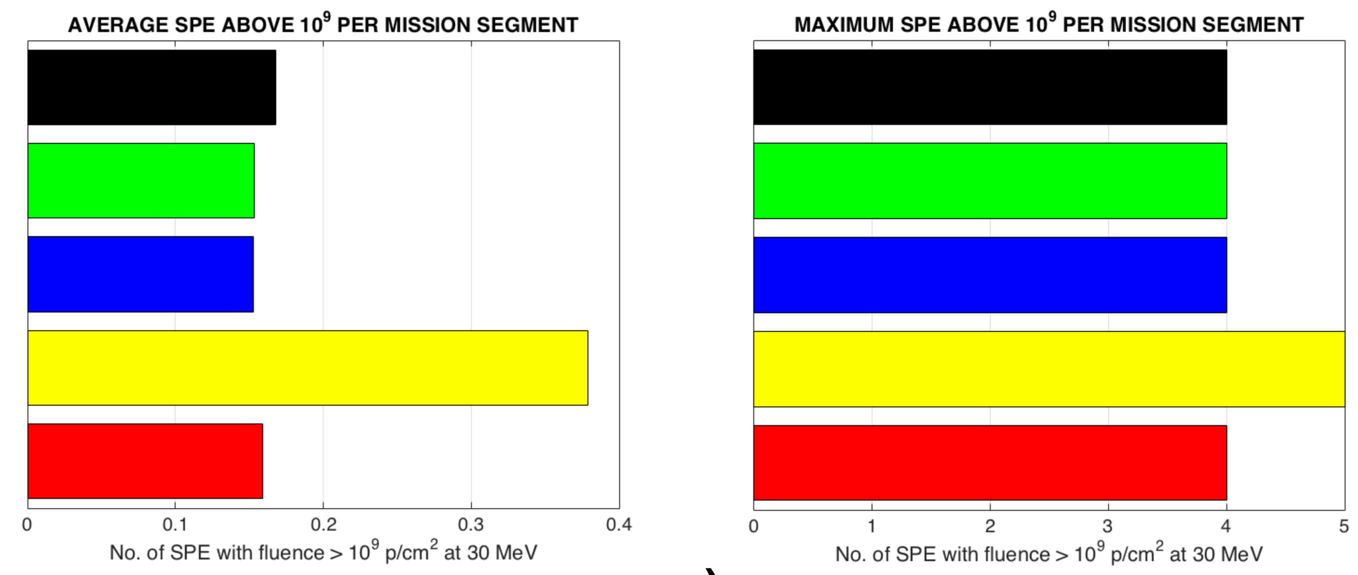



**Fig. 3:** SPE rates for different proposed Mars mission segments with GEO shown for comparison. **a)** Shows average overall SPE per each mission and **b)** only $10^9$ events, which could result in doses that endanger the crew. While **c)** shows maximum possible $10^9$ SPEs for each mission profile. Results shown here are for 100k runs of the Monte Carlo aspect of the model.




b) c)

## Conclusions

The SPE likelihood model outside of LEO showed the risk and magnitude inherent in using a Venus swing-by return from Mars to Earth. This trajectory choice more than doubles the average number of SPEs that could hit the spacecraft during the transit, increasing the risk of high magnitude events, which increases the risk of mission consequences due to SPEs. In order to better mitigate this risk, shielding and forecasting will need to be a part of any radiation protection plan for a Mars mission. Future work on this model includes integrating additional SPE cases, evaluating more specific missions, and integration with existing models.

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